Exploring flavor structure of supersymmetry breaking at B factories

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We investigate quark flavor signals in three different supersymmetric models, minimal supergravity, the SU(5) SUSY GUT with right handed neutrinos, and the minimal supersymmetric standard model with U(2) flavor symmetry, in order to study the physics potential of the present and future B factories. We evaluate CP asymmetries in various B decay modes, Δm_{B_s}, Δm_{B_d}, and ε_K. The allowed regions of the CP asymmetry in $B\to J/\psi K_S$ and $\Delta m_{B_s}/\Delta m_{B_d}$ are different for the three models so that precise determinations of these observables in near future experiments are useful to distinguish the three models. We also investigate possible deviations from the standard model predictions of CP asymmetries in other B decay modes. In particular, a large deviation is possible for the U(2) model. The consistency check of the unitarity triangle including $B\to\pi\pi,\rho\pi,D^{(*)}K^{(*)},D^{(*)}\pi,D^*\rho$, and so on, at future high luminosity e^+e^- B factories and hadronic B experiments is therefore important to distinguish flavor structures of different supersymmetric models.

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I. INTRODUCTION

The recent developments in B physics are remarkable. Both the Belle experiment at KEK and the BaBar experiment at SLAC observed large CP violation in $B\to J/\psi K_S$ and related modes. These observations are the first discovery of CP violation out of the kaon system [1,2]. The results are consistent with the Kobayashi-Maskawa mechanism [3] of CP violation in the three-generation standard model (SM). In the coming years, we expect much improvement in the measurements of CP violation and rare decay processes at the asymmetric B factories. In addition, the magnitude of the B_s-$\overline{B}_s$ mixing will be determined at the Fermilab Tevatron experiments [4]. It will be clear in a few years whether or not the Cabibbo-Kobayashi-Maskawa (CKM) matrix is the main source of flavor mixing and CP violation in the quark sector.

In the future, B physics is expected to play an even more important role in precisely determining the flavor structure of the SM and searching for possible new physics effects beyond the SM. CERN LHC-B [5] and BTeV [6] experiments are planned to provide very precise information on the angles of the unitarity triangle from B_d and B_s decays at hadron machines. As for e^+e^- asymmetric colliders, both KEK and SLAC are considering increasing the luminosity by one to two orders of magnitude by the time that these hadron experiments will be carried out [7,8]. With luminosity of 10^{35}–10^{36} cm^{-2} s^{-1}, the super B factories will provide us with 10^9–10^{10} $B\overline{B}$ pairs in a year. Then, we shall have good opportunities to explore new physics from observations of CP asymmetries and rare B decay processes.

Among various candidates of new physics beyond the SM, supersymmetry (SUSY) is the most interesting one. Although the main motivation for introducing SUSY is to solve the hierarchy problem, namely to give a justification to the electroweak scale, which is much smaller than the Planck scale, flavor physics can provide important information on SUSY models. In SUSY models, mass matrices of SUSY partners of the quarks and the leptons are new sources of the flavor mixing. Since these mass matrices are determined from SUSY breaking terms in the Lagrangian, their flavor structures reflect the SUSY breaking mechanism and interactions present between the scale of the SUSY breaking and the electroweak scale. Future B physics is therefore very important to discriminate various SUSY breaking scenarios. It can play a more important role if CERN Large Hadron collider (LHC) experiments discover SUSY particles, in which case we can make more precise predictions for flavor signals based on a particular scenario.

In this paper, we investigate SUSY effects on B physics based on three different SUSY models, namely (1) the minimal supergravity (mSUGRA) model, (2) the SU(5) SUSY grand unified theory (GUT) with right-handed neutrinos, and (3) the SUSY model with U(2) flavor symmetry [9,10]. We focus on the new physics search through the consistency test of the unitarity triangle. We address two questions. First, we ask whether these models can be distinguished from the SM in the near future by measuring the CP asymmetry of B

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$\to J/\psi K_S$ and the B_s-$\overline{B_s}$ mixing. Second, we consider impacts of other angle measurements of the unitarity triangle in the era of LHC-B/BTeV and an e^+e^- super B factory when the above two observables are precisely determined. We analyze the three models in the same fashion, so that we can clearly show the potential of future B physics. There are already many analyses in the literature for each of the three models [9–15], but here we make a systematic treatment to show that various measurements in B physics are in fact useful to distinguish different SUSY models. We show that the allowed region of $\Delta m_{B_s}/\Delta m_{B_d}$ is quite different from the SM prediction for the SU(5) SUSY GUT with right-handed neutrinos and the U(2) model, whereas the deviation is small for the mSUGRA. Furthermore, the GUT and the U(2) model can be distinguished when we measure CP asymmetries of decay modes such as $B\to\pi\pi,\rho\pi,D^{(*)}K^{(*)},D^{(*)}\pi$, and $D^*\rho$.

This paper is organized as follows. The three models are introduced in Sec. II. The B_d-$\overline{B_d}$ mixing, the B_s-$\overline{B_s}$ mixing, the CP violating parameter in the K^0-$\overline{K^0}$ mixing (ε_K), and CP violations in various B decays are discussed in Sec. III. The numerical results of these observables are presented in Sec. IV. Our conclusion is given in Sec. V.

II. MODELS

A. The minimal supersymmetric standard model

The minimal supersymmetric standard model (MSSM) is an $\mathrm{SU}(3)_\mathrm{C}\times\mathrm{SU}(2)_\mathrm{L}\times\mathrm{U}(1)_\mathrm{Y}$ supersymmetric gauge theory with the SUSY being softly broken. The MSSM matter contents are the following chiral superfields:

$$\begin{aligned}
&Q_i(3,2,\tfrac{1}{6}),\quad \overline{U}_i(\overline{3},1,-\tfrac{2}{3}),\quad \overline{D}_i(\overline{3},1,\tfrac{1}{3}),\\
&L_i(1,2,-\tfrac{1}{2}),\quad \overline{E}_i(1,1,1),\\
&H_1(1,2,-\tfrac{1}{2}),\quad H_2(1,2,\tfrac{1}{2}),
\end{aligned}\tag{1}$$

where the gauge quantum numbers are shown in parentheses and $i=1,2,3$ is a generation index. Assuming R-parity invariance and renormalizability, we can write the MSSM superpotential as

$$\begin{aligned}
\mathcal{W}_{\mathrm{MSSM}}=&f_D^{ij}\overline{D}_iQ_jH_1+f_U^{ij}\overline{U}_iQ_jH_2\\
&+f_E^{ij}\overline{E}_iL_jH_1\\
&+\mu H_1H_2.
\end{aligned}\tag{2}$$

The soft SUSY breaking is described by the following Lagrangian:

$$\begin{aligned}
-\mathcal{L}_{\mathrm{soft}}=&(m_Q^2)^i{}_j\tilde{q}_i\tilde{q}^{\dagger j}+(m_D^2)_i{}^j\tilde{d}^{\dagger i}\tilde{d}_j+(m_U^2)_i{}^j\tilde{u}^{\dagger i}\tilde{u}_j\\
&+(m_E^2)^i{}_j\tilde{e}_i\tilde{e}^{\dagger j}+(m_L^2)_i{}^j\tilde{l}^{\dagger i}\tilde{l}_j+\Delta_1^2h_1^\dagger h_1+\Delta_2^2h_2^\dagger h_2\\
&-(B\mu h_1h_2+\mathrm{H.c.})+(A_D^{ij}\tilde{d}_i\tilde{q}_jh_1+A_U^{ij}\tilde{u}_i\tilde{q}_jh_2\\
&+A_L^{ij}\tilde{e}_i\tilde{l}_jh_1+\mathrm{H.c.})+\frac{M_1}{2}\overline{\tilde{B}}\tilde{B}+\frac{M_2}{2}\overline{\tilde{W}}\tilde{W}+\frac{M_3}{2}\overline{\tilde{g}}\tilde{g},
\end{aligned}\tag{3}$$

where $\tilde{q}_i$, $\tilde{u}_i$, $\tilde{d}_i$, $\tilde{l}_i$, $\tilde{e}_i$, h_1, and h_2 are the corresponding scalar components of the chiral superfields, and $\tilde{B}$, $\tilde{W}$, and $\tilde{g}$ denote $\mathrm{U}(1)_\mathrm{Y}$, $\mathrm{SU}(2)_\mathrm{L}$, and $\mathrm{SU}(3)_\mathrm{C}$ gauge fermions, respectively.

B. Flavor structure of the soft breaking terms

Although the Yukawa couplings are the only source of the flavor mixing in the SM, the mass terms and the trilinear scalar coupling terms (A terms) of squarks and sleptons in Eq. (3) may induce additional flavor mixings in the MSSM.

The Yukawa couplings f's in Eq. (2) are constrained to reproduce the known quark and lepton masses and the CKM matrix. On the other hand, the soft breaking terms, their flavor structures in particular, are rather unconstrained at first sight, apart from the naturalness condition that they should be within the TeV scale. As is well known, however, unless some specific structure is assumed in the soft breaking terms, the sfermion-exchanging contributions to flavor changing neutral current (FCNC) processes such as the K^0-$\overline{K^0}$mixing and the $\mu\to e\gamma$ decay are too large to satisfy the experimental limits, if the squark and slepton masses are below a few TeV. There are several ways to avoid this problem.

One is to assume a SUSY breaking (and its mediation) mechanism in which the universality of the soft breaking terms are ensured. In other words, mass degeneracy for the sfermions with the same electric charge and chirality, and proportionality of the A terms to the Yukawa coupling constants are required to suppress FCNC processes. Phenomenology of models with the universality further depends on the energy scale where the SUSY breaking is generated, because the universality in the sfermion sector is vitiated due to radiative corrections induced by the Yukawa couplings.

It is convenient to use renormalization group (RG) equations in order to trace these radiative corrections. The universality in the soft breaking terms is imposed on the boundary conditions of the RG equations at the energy scale of the SUSY breaking. If the energy scale of the SUSY breaking is close to the electroweak scale, the RG evolution is tiny and the universality is practically maintained. The gauge mediated SUSY breaking model [16] is of this kind, and its flavor phenomenology is quite similar to that of the SM.

If the energy scale of the SUSY breaking is far above the electroweak scale, the RG evolution is sizable and the universality is lost. Though not exactly universal, flavor physics is still under control in this kind of models in the sense that the origin of the flavor mixing only resides in the Yukawa couplings. The flavor mixing in the squark sector is determined by the quark masses and the CKM matrix. On the other hand, the flavor mixing in the slepton sector is ruled by the lepton couplings in the superpotential including Majorana mass terms of right-handed neutrinos if existing. The mSUGRA discussed in Sec. II C is a model in this class.

Embedded in a GUT, the above situation is modified if the energy scale of the SUSY breaking is higher than the GUT scale. Since the GUT interactions obscure the distinction between the quark flavors and the lepton flavors, the lepton flavor mixing in the Yukawa couplings affects the squark sector. We shall examine an SU(5) SUSY GUT with right-handed neutrinos among models of this kind in Sec. II D.

Another way to suppress the FCNC processes is to rely on a flavor (or horizontal) symmetry. It is obvious that the flavor symmetry, whatever it is, should be broken because the Yukawa couplings have no such symmetry. The symmetry breaking must be taken so that the observed quark and lepton masses and their mixings are reproduced. Even though this constraint is imposed, there are several choices for the flavor symmetry and its breaking pattern. The flavor phenomenology heavily depends on them. In Sec. II E we shall consider a model with U(2) flavor symmetry among the possibilities.

C. The minimal supergravity model

The mSUGRA consists of the observable sector, i.e., the MSSM, and a hidden sector. These two sectors are only interconnected by the gravitation. The SUSY is assumed to be spontaneously broken in the hidden sector, and the soft breaking terms in Eq. (3) are induced through the gravitational interaction in the following manner:

$$
\begin{aligned}
&(m_Q^2)^i{}_j=(m_E^2)^i{}_j=m_0^2\delta^i{}_j,\\
&(m_D^2)_i{}^j=(m_U^2)_i{}^j=(m_L^2)_i{}^j=m_0^2\delta_i{}^j,\\
&\Delta_1^2=\Delta_2^2=m_0^2,\\
&A_D^{ij}=m_0A_0f_D^{ij},\quad A_U^{ij}=m_0A_0f_U^{ij},\\
&A_L^{ij}=m_0A_0f_L^{ij},\\
&M_1=M_2=M_3=M_{1/2},
\end{aligned}
\tag{4}
$$

where we assume the GUT relation among the gaugino masses. The above relations are applied at the energy scale where the soft breaking terms are induced by the gravitational interaction. We identify this scale with the GUT scale $(M_X\simeq 2\times 10^{16}\ \text{GeV})$ for simplicity.

The soft breaking terms at the electroweak scale are determined by solving RG equations with the initial conditions defined in Eq. (4).

D. The SU(5) SUSY GUT with right-handed neutrinos

The measurements of the three gauge coupling constants at the CERN e^+e^- collider LEP, SLAC Linear Collider (SLC), and other experiments support the idea of the supersymmetric grand unification. Furthermore, there is clear evidence of neutrino oscillations in the atmospheric [17] and the solar [18] neutrino experiments. Guided by these experimental results, SU(5) SUSY GUT with right-handed neutrino has been studied. In particular, the relationship between quark flavor signals and the neutrino oscillations has been investigated in Refs. [12–14]. A large flavor mixing in the neutrino sector can include a squark mixing in the right-handed down-type squark sector. In Ref. [12], the quark flavor signals are studied for various neutrino oscillation scenarios. In Ref. [13], effects of CP violating phases in the GUT Yukawa coupling constants are taken into account. It is shown in these papers that large contributions to ε_K and the $\mu\to e\gamma$ decay can arise from the new source of flavor mixing in the neutrino sector. These analyses are extended to the case of a GUT model with realistic fermion mass matrices in Ref. [14]. Here we follow the analysis of Ref. [14] and we give a brief description of the model.

The Yukawa couplings and Majorana masses of the right-handed neutrinos in the model are described by the following superpotential:

$$
\begin{aligned}
\mathcal{W}_{\mathrm{SU}(5)\nu_R}=&\frac{1}{8}\epsilon_{abcde}(\lambda_U)^{ij}(T_i)^{ab}(T_j)^{cd}H^e\\
&+(\lambda_D)^{ij}(\overline{F}_i)_a(T_j)^{ab}\overline{H}_b+(\lambda_N)^{ij}\overline{N}_i(\overline{F}_j)_aH^a\\
&+\frac{1}{2}(M_N)^{ij}\overline{N}_i\overline{N}_j,
\end{aligned}
\tag{5}
$$

where i and j are generation indices, while a,b,c,d, and e are SU(5) indices. ϵ_{abcde} denotes the totally antisymmetric tensor of the SU(5). T_i, $\overline{F}_i$, and $\overline{N}_i$ are **10**, $\overline{\mathbf{5}}$, and **1** representations of the SU(5) gauge group, respectively. T_i contains Q_i, $\overline{U}_i$, and $\overline{E}_i$ in Eq. (1), and $\overline{F}_i$ includes $\overline{D}_i$ and L_i. H and $\overline{H}$ are Higgs superfields in **5** and $\overline{\mathbf{5}}$ representations, respectively. H consists of $H_C(\mathbf{3},\mathbf{1},-\frac{1}{3})$ and H_2, and $\overline{H}$ does $\overline{H}_C(\overline{\mathbf{3}},\mathbf{1},\frac{1}{3})$ and H_1. $(\lambda_U)^{ij}$, $(\lambda_D)^{ij}$, and $(\lambda_N)^{ij}$ are the Yukawa coupling matrices, and $(M_N)^{ij}$ is the Majorana mass matrix. In addition to the above superpotential, we also need a superpotential for Higgs superfields, $\mathcal{W}_H(H,\overline{H},\Sigma)$, where Σ^a_b is a **24** representation of the SU(5) group. It is assumed to develop a vacuum expectation value (VEV) as $\langle\Sigma^a_b\rangle=\mathrm{diag}(\frac{1}{3},\frac{1}{3},\frac{1}{3},-\frac{1}{2},-\frac{1}{2})v_G$ at the GUT scale and breaks the SU(5) symmetry to $\mathrm{SU}(3)_\mathrm{C}\times\mathrm{SU}(2)_\mathrm{L}\times\mathrm{U}(1)_\mathrm{Y}$.

The supermultiplets whose masses are of order of the GUT scale such as H_C and $\overline{H}_C$ can be integrated out below the GUT scale. Then, the effective theory below the GUT scale is the MSSM with the right-handed neutrino supermultiplets, and its superpotential is given as

$$
\mathcal{W}_{\mathrm{MSSM}\nu_R}=\mathcal{W}_{\mathrm{MSSM}}+(f_N)^{ij}\overline{N}_iL_jH_2+\frac{1}{2}(M_N)^{ij}\overline{N}_i\overline{N}_j,
\tag{6}
$$

where the Yukawa coupling matrices are related to those in Eq. (5) as $(f_U)^{ij}=(\lambda_U)^{ij}$, $(f_D)^{ij}=(f_E^T)^{ij}=(\lambda_D)^{ij}$, and $(f_N)^{ij}=(\lambda_N)^{ij}$ in the leading order approximation.

In the energy region lower than the Majorana mass scale $(\equiv M_R)$, the singlet supermultiplets are integrated out, and the resulting superpotential is the sum of $\mathcal{W}_{\mathrm{MSSM}}$ in Eq. (2) and the following higher dimensional term:

$$
\begin{aligned}
\Delta\mathcal{W}_\nu&=-\frac{1}{2}(K_\nu)^{ij}(L_iH_2)(L_jH_2),\\
K_\nu&=(f_N^T)^{ik}\left(\frac{1}{M_N}\right)_{kl}(f_N)^{lj}.
\end{aligned}
\tag{7}
$$

This term yields the neutrino masses below the electroweak scale as

$$(m_\nu)^{ij}=(K_\nu)^{ij}\langle h_2\rangle^2. \tag{8}$$

The above neutrino mass matrix is related to the observable neutrino mass eigenvalues and the Maki-Nakagawa-Sakata (MNS) mixing matrix [19] as

$$(m_\nu)^{ij}=(V^*_{\rm MNS})^i{}_k m_\nu{}^k (V^\dagger_{\rm MNS})_k{}^j \tag{9}$$

in the basis in which the charged lepton mass matrix is diagonal.

As is mentioned above, the superpotential in Eq. (5) predicts that

$$(f_E)^{ij}=(f_D)^{ji} \tag{10}$$

at the GUT scale. It is well-known that the mass ratios of the down-type quarks to the charged leptons in the first and the second generations cannot be explained by this relation although it reasonably works for the third generation. This, however, is not a fatal flaw of SU(5) GUTs because there are several ways to overcome this shortcoming. For example, higher dimensional operators with Σ^a_b may contribute differently to the Yukawa coupling matrices of the down-type quarks and the charged leptons.

In Ref. [14], quark FCNC processes, lepton flavor violation processes, and the muon anomalous magnetic moment were calculated in this model. To account for quark and lepton mass ratios, the following higher dimensional operator was introduced:

$$\Delta\mathcal{W}_{{\rm SU}(5)\nu_R}=\frac{(\kappa_D)^{ij}}{M_P}(\overline{F}_i)_a\Sigma^a_b(T_j)^{bc}\overline{H}_c, \tag{11}$$

where M_P is the Planck mass ($M_P\simeq 2\times 10^{18}$ GeV). Consequently, Eq. (10) is modified to

$$(f_E)^{ij}=(f_D)^{ji}-\frac{5}{6}\xi(\kappa_D)^{ji}, \tag{12}$$

where $\xi=v_G/M_P\simeq 0.01$. Taking the Majorana mass matrix proportional to the unit matrix $[(M_N)^{ij}=M_R\delta^{ij}]$ for simplicity, Baek *et al.* [14] showed that the flavor mixings of the squark and slepton sectors were determined by the CKM matrix, the MNS matrix, and two additional mixing matrices related to the down-type quark and the charged lepton Yukawa coupling constants. As long as we take the large mixing Mikheyev-Smirnov-Wolfenstein (MSW) solution for the solar neutrino anomaly, the SUSY effect becomes large for ε_K and $B(\mu\to e\gamma)$. In this paper we follow Ref. [14] but consider the special case that the two additional mixing matrices are equal to the unit matrix because the general features mentioned above do not change by this simplification.

In order to calculate the FCNC processes we need to specify the soft breaking terms. The SU(5) invariant soft breaking terms are written as

$$\begin{aligned}-\mathcal{L}^{\rm SU(5)}_{\rm soft}=&(m^2_T)_i{}^j(\tilde{T}^{i*})_{ab}(\tilde{T}_j)^{ab}+(m^2_{\overline{F}})_i{}^j(\tilde{\overline{F}}{}^{i*})^a(\tilde{\overline{F}}_j)_a+(m^2_{\overline{N}})_i{}^j\tilde{\overline{N}}{}^{i*}\tilde{\overline{N}}_j+(m^2_H)H^*{}_aH^a+(m^2_{\overline{H}})\overline{H}^{*a}\overline{H}_a\\&+\left\{\frac{1}{8}\epsilon_{abcde}(\tilde{\lambda}_U)^{ij}(\tilde{T}_i)^{ab}(\tilde{T}_j)^{cd}H^e+(\tilde{\lambda}_D)^{ij}(\tilde{\overline{F}}_i)_a(\tilde{T}_j)^{ab}\overline{H}_b+(\tilde{\lambda}_N)^{ij}\tilde{\overline{N}}_i(\tilde{\overline{F}}_j)_aH^a+\frac{1}{2}(\tilde{M}_N)^{ij}\tilde{\overline{N}}_i\tilde{\overline{N}}_j+\text{H.c.}\right\}\\&+\frac{1}{M_P}[(\tilde{\kappa}_d)^{ij}(\tilde{\overline{F}}{}^i)_a\Sigma^a{}_b(\tilde{T}^j)^{bc}\overline{H}_c+\text{H.c.}]+\frac{1}{2}M_5\overline{\tilde{G}}_5\tilde{G}_5,\end{aligned} \tag{13}$$

where $\tilde{T}^i$, $\tilde{\overline{F}}{}^i$, and $\tilde{\overline{N}}{}^i$ are the scalar components of T^i, $\overline{F}^i$, and $\overline{N}^i$, respectively; H and $\overline{H}$ stand for the corresponding scalar components of the superfields denoted by the same symbols; and $\tilde{G}_5$ represents the SU(5) gaugino. We assume that the soft breaking terms are universally generated at the Planck scale, i.e.,

$$\begin{aligned}&(m^2_T)_i{}^j=(m^2_{\overline{F}})_i{}^j=(m^2_{\overline{N}})_i{}^j=m_0^2\delta_i^j,\\&(\tilde{\lambda})^{ij}=m_0A_0(\lambda)^{ij},\quad(\lambda=\lambda_U,\lambda_D,\lambda_N),\\&(\tilde{\kappa}_D)^{ij}=m_0A_0(\kappa_D)^{ij},\\&M_5=M_{1/2}.\end{aligned} \tag{14}$$

These equations serve as a set of boundary conditions of RG equations at the Planck scale.

We solve the RG equations of the SU(5) SUSY GUT from the Planck scale to the GUT scale, then those of MSSM with right-handed neutrinos between the GUT scale and M_R. Finally, the squark and slepton mass matrices are obtained by the RG equations of the MSSM below M_R.

E. A model with U(2) flavor symmetry

It is possible that the family structure of the quarks and the leptons is explained by some flavor symmetry. Although U(3) is a natural candidate of the flavor symmetry, it is badly broken by the top Yukawa coupling. It is therefore legitimate to choose a U(2) symmetric model in order to study the flavor problem in the MSSM.

In this framework, the quark and lepton supermultiplets in the first and the second generations transform as doublets under the U(2) flavor symmetry. Each of these doublets carries a positive unit charge of the U(1) subgroup. The quark and lepton supermultiplets in the third generation and the Higgs supermultiplets are totally singlet under the U(2). In addition to the ordinary matter fields, we introduce the following superfields: a doublet $\Phi^i(-1)$, a symmetric tensor $S^{ij}(-2)$, and an antisymmetric tensor $A^{ij}(-2)$, where i and j run from 1 to 2, and the numbers in the parentheses represent the U(1) charges [10].

The U(2) invariant superpotential relevant to the quark Yukawa couplings is given as follows:

$$\begin{aligned}\mathcal{W}_{\mathrm{U}(2)}=&y_U\bigg(\overline{U}_3Q_3H_2+\frac{b_U}{M_F}\Phi^i\overline{U}_iQ_3H_2+\frac{c_U}{M_F}\overline{U}_3\Phi^iQ_iH_2\\&+\frac{d_U}{M_F}S^{ij}\overline{U}_iQ_jH_2+\frac{a_U}{M_F}A^{ij}\overline{U}_iQ_jH_2\bigg)\\&+y_D\bigg(\overline{D}_3Q_3H_1+\frac{b_D}{M_F}\Phi^i\overline{D}_iQ_3H_1\\&+\frac{c_D}{M_F}\overline{D}_3\Phi^iQ_iH_1+\frac{d_D}{M_F}S^{ij}\overline{D}_iQ_jH_1\\&+\frac{a_D}{M_F}A^{ij}\overline{D}_iQ_jH_1\bigg),\end{aligned}\tag{15}$$

where M_F is the scale of the flavor symmetry, and y_Q, a_Q, b_Q, c_Q, and d_Q ($Q=U,D$) are dimensionless coupling constants. In Eq. (15) we neglected dimension five and higher dimensional operators in the superpotential. Absolute values of the above dimensionless coupling constants except for y_D are supposed to be of $O(1)$.

The successful breaking pattern of the U(2) symmetry is that

$$\mathrm{U}(2)\to\mathrm{U}(1)\to\mathbb{1}\ (\text{no symmetry}),\tag{16}$$

where the first breaking is induced by VEVs of Φ^i and S^{ij}, and a VEV of A^{ij} brings about the second one. The VEVs are given as

$$\frac{\langle\Phi^i\rangle}{M_F}=\delta^{i2}\epsilon_\Phi,\quad\frac{\langle S^{ij}\rangle}{M_F}=\delta^{i2}\delta^{j2}\epsilon_S,\quad\frac{\langle A^{ij}\rangle}{M_F}=\epsilon^{ij}\epsilon',\tag{17}$$

where ϵ_Φ and ϵ' are taken to be real without loss of generality. Note that $\langle S^{ij}\rangle$ is chosen so that it leaves a U(1) unbroken. Hierarchical relations among the VEVs that $\epsilon'\ll\epsilon_\Phi\sim|\epsilon_S|\ll1$ are assumed in order to reproduce the quark masses and the quark mixing angles.

With the above VEVs, we obtain the following quark Yukawa couplings:

$$(f_Q^{ij})=y_Q\begin{pmatrix}0&a_Q\epsilon'&0\\-a_Q\epsilon'&d_Q\epsilon&b_Q\epsilon\\0&c_Q\epsilon&1\end{pmatrix},\quad Q=U,D,\tag{18}$$

where we use $\epsilon\equiv\epsilon_\Phi=\epsilon_S$, which is valid providing appropriate redefinitions of the coupling constants in Eq. (15). Equation (18) is applied at the GUT scale where we assume that the symmetry breaking sequence in Eq. (16) occurs. The parameters in Eq. (18) are determined so that the known quark masses and mixing are reproduced taking the RG evolution into account.

The U(2) symmetry constrains the soft breaking terms as well as the supersymmetric terms. The U(2) invariant soft breaking terms relevant to squark masses are

$$\begin{aligned}-\mathcal{L}_m=\sum_{f=q,u,d}m_0^{f2}\bigg[&\tilde{f}^{*i}\tilde{f}_i+a_f^3\tilde{f}^{*3}\tilde{f}_3+\frac{a_f^\phi}{M_F}\tilde{f}^{*3}\phi^i\tilde{f}_i\\&+\frac{a_f^{\phi*}}{M_F}\phi_i^*\tilde{f}^{i*}\tilde{f}_3+\frac{a_f^{\phi\phi}}{M_F}\phi_i^*\tilde{f}^{i*}\phi^j\tilde{f}_j\\&+\frac{a_f^{SS}}{M_F}S_{ik}^*\tilde{f}^{k*}S^{ij}\tilde{f}_j\bigg],\end{aligned}\tag{19}$$

where a_f's are dimensionless coupling constants of $O(1)$, and shown are the terms that yield squark masses of $O(\epsilon^2)$ or larger when the flavor symmetry breaking takes place. The squark mass matrices stemming from Eq. (19) are parametrized as

$$m_X^2=m_0^{X2}\begin{pmatrix}1&0&0\\0&1+r_{22}^X\epsilon^2&r_{23}^X\epsilon\\0&r_{23}^{X*}\epsilon&r_{33}^X\end{pmatrix},\quad X=Q,U,D,\tag{20}$$

where r^X's are constant parameters of $O(1)$.

As for the A terms, it turns out that they have the same hierarchical structure as the Yukawa couplings in Eq. (18):

$$(A_Q^{ij})=A_Q^0\begin{pmatrix}0&\tilde{a}_Q\epsilon'&0\\-\tilde{a}_Q\epsilon'&\tilde{d}_Q\epsilon&\tilde{b}_Q\epsilon\\0&\tilde{c}_Q\epsilon&1\end{pmatrix},\quad Q=U,D.\tag{21}$$

In general, though being of $O(1)$, $\tilde{a}_Q$, $\tilde{b}_Q$, $\tilde{c}_Q$, and $\tilde{d}_Q$ take different values from the corresponding parameters in Eq. (18). Therefore we expect no exact universality of the A terms in this model.

The soft SUSY breaking terms at the electroweak scale are given by solving the RG equations of the MSSM with the boundary conditions in Eqs. (20) and (21) at the GUT scale.

III. OBSERVABLES

The observables considered in the following are the CP violation parameter ε_K in the K^0-$\overline{K}^0$ mixing, B_d-$\overline{B}_d$ and B_s-$\overline{B}_s$ mass splittings Δm_{B_d} and Δm_{B_s}, respectively, and

CP asymmetries in various B decay modes.

The B_d-$\overline{B}_d$, B_s-$\overline{B}_s$, and K^0-$\overline{K}^0$ mixings are described by the effective Lagrangian of the following form:

$$\begin{aligned}\mathcal{L}=&C_{LL}(\overline{q}_L^\alpha\gamma^\mu Q_{L\alpha})(\overline{q}_L^\beta\gamma_\mu Q_{L\beta})\\&+C_{RR}(\overline{q}_R^\alpha\gamma^\mu Q_{R\alpha})(\overline{q}_R^\beta\gamma_\mu Q_{R\beta})+C_{LR}^{(1)}(\overline{q}_R^\alpha Q_{L\alpha})(\overline{q}_L^\beta Q_{R\beta})\\&+C_{LR}^{(2)}(\overline{q}_R^\alpha Q_{L\beta})(\overline{q}_L^\beta Q_{R\alpha})+\tilde{C}_{LL}^{(1)}(\overline{q}_R^\alpha Q_{L\alpha})(\overline{q}_R^\beta Q_{L\beta})\\&+\tilde{C}_{LL}^{(2)}(\overline{q}_R^\alpha Q_{L\beta})(\overline{q}_R^\beta Q_{L\alpha})+\tilde{C}_{RR}^{(1)}(\overline{q}_L^\alpha Q_{R\alpha})(\overline{q}_L^\beta Q_{R\beta})\\&+\tilde{C}_{RR}^{(2)}(\overline{q}_L^\alpha Q_{R\beta})(\overline{q}_L^\beta Q_{R\alpha}),\end{aligned}\tag{22}$$

where $(q,Q)=(d,b)$, (s,b), and (d,s) for the B_d-$\overline{B}_d$, B_s-$\overline{B}_s$, and K^0-$\overline{K}^0$ mixings, respectively. The suffices α and β are color indices. The Wilson coefficients C's are obtained by calculating box diagrams. See Ref. [14] for explicit formulas of the coefficients. The mixing matrix elements $M_{12}(B_d)$, $M_{12}(B_s)$, and $M_{12}(K)$ are given as

$$M_{12}(P)=-\frac{1}{2m_P}\langle P|\mathcal{L}|\overline{P}\rangle,\tag{23}$$

where $P=B_d, B_s, K^0$.

In the SM, the flavor changes only occur in the interaction with the left-handed quarks, so that M_{12} is dominated by the C_{LL} term for all three mesons. The situation is the same in the mSUGRA, since the flavor mixing in the squark sector is induced by the running effect and hence takes place only in the left-handed squark sector. In the SU(5) SUSY GUT with right-handed neutrinos and the U(2) model, on the other hand, there are sources of squark flavor mixing other than the CKM matrix. In the SU(5) SUSY GUT with right-handed neutrinos, flavor mixing in the right-handed down-type squark sector is induced due to the Yukawa coupling matrix of the neutrinos through the running between the GUT and the Planck scales. In the U(2) model, the squark mass matrices contain more free parameters. Consequently, flavor mixing is possible in both the left-handed and the right-handed squark sectors and the mixing matrices can be different from the CKM matrix. In the latter two models all the Wilson coefficients in Eq. (22) are relevant.

We parametrize the matrix elements of the operators in Eq. (22) as

$$\langle K^0|(\overline{d}_L^\alpha\gamma^\mu s_{L\alpha})(\overline{d}_L^\beta\gamma_\mu s_{L\beta})|\overline{K}^0\rangle=\frac{2}{3}m_K^2f_K^2B_K,\tag{24a}$$

$$\langle K^0|(\overline{d}_R^\alpha s_{L\alpha})(\overline{d}_L^\beta s_{R\beta})|\overline{K}^0\rangle=\frac{1}{2}\left(\frac{m_K}{m_s+m_d}\right)^2m_K^2f_K^2B_K^{LR(1)},\tag{24b}$$

$$\langle K^0|(\overline{d}_R^\alpha s_{L\beta})(\overline{d}_L^\beta s_{R\alpha})|\overline{K}^0\rangle=\frac{1}{6}\left(\frac{m_K}{m_s+m_d}\right)^2m_K^2f_K^2B_K^{LR(2)},\tag{24c}$$

$$\langle K^0|(\overline{d}_L^\alpha s_{R\alpha})(\overline{d}_L^\beta s_{R\beta})|\overline{K}^0\rangle=-\frac{5}{12}\left(\frac{m_K}{m_s+m_d}\right)^2m_K^2f_K^2\tilde{B}_K^{RR(1)},\tag{24d}$$

$$\langle K^0|(\overline{d}_L^\alpha s_{R\beta})(\overline{d}_L^\beta s_{R\alpha})|\overline{K}^0\rangle=\frac{1}{12}\left(\frac{m_K}{m_s+m_d}\right)^2m_K^2f_K^2\tilde{B}_K^{RR(2)},\tag{24e}$$

where B_K, $B_K^{LR(1,2)}$, and $\tilde{B}_K^{RR(1,2)}$ are bag parameters of $O(1)$, which have been calculated by the lattice QCD method [20]. It can be seen that the matrix elements of the scalar operators are enhanced by a factor $\sim(m_K/m_s)^2$ for the K^0-$\overline{K}^0$ mixing. For B^0-$\overline{B}^0$ mixing cases, the corresponding factor is $\sim(m_B/m_b)^2$ so that the enhancement is less significant. In the SU(5) SUSY GUT with right-handed neutrinos and the U(2) model, the C_{LR} and/or $\tilde{C}_{RR}$ terms can significantly contribute to $M_{12}(K)$ because of this enhancement in the matrix elements.

We can express ε_K, Δm_{B_d}, and Δm_{B_s} in terms of M_{12} as

$$\varepsilon_K=\frac{e^{i\pi/4}\,\mathrm{Im}\,M_{12}(K)}{\sqrt{2}\Delta m_K},\tag{25}$$

$$\Delta m_{B_d}=2|M_{12}(B_d)|,\tag{26}$$

$$\Delta m_{B_s}=2|M_{12}(B_s)|.\tag{27}$$

The CP asymmetry in $B\to J/\psi K_S$, $A_{CP}^{\mathrm{mix}}(B\to J/\psi K_S)$ is defined as

$$\frac{\Gamma[B_d(t)\to J/\psi K_S]-\Gamma[\overline{B}_d(t)\to J/\psi K_S]}{\Gamma[B_d(t)\to J/\psi K_S]+\Gamma[\overline{B}_d(t)\to J/\psi K_S]}=-A_{CP}^{\mathrm{mix}}(B\to J/\psi K_S)\sin\Delta m_{B_d}t.\tag{28}$$

This asymmetry is given by the phase of $M_{12}(B_d)$ as

$$A_{CP}^{\mathrm{mix}}(B\to J/\psi K_S)=\sin\phi_M,\tag{29}$$

where ϕ_M is defined as $e^{i\phi_M}=M_{12}(B_d)/|M_{12}(B_d)|$. In the present analysis we assume that the tree-level diagram dominates the $B_d(\overline{B}_d)\to J/\psi K_S$ decay so that no new phase appears in the decay amplitude.[1] Experimentally, $\sin\phi_M$ can be determined by combining decay modes with the $b\to c\overline{c}s$ transition such as $B_d\to J/\psi K_S$, $B_d\to J/\psi K_L$, and $B_d\to\psi' K_S$.

In order to constrain new physics from the consistency check on the closure of the unitarity triangle, depicted in Fig. 1, it is important to measure the angles other than ϕ_M. There are several theoretically clean ways to determine these angles. In the SM, $2\phi_1$ is given by ϕ_M, and $\sin 2\phi_2$ is obtained from the isospin analysis of $B\to\pi\pi$ [21] and the

[1]In the U(2) model, in particular, there might be sizable contributions to the decay amplitudes with new CP phases. In such a case a direct CP asymmetry may be observed.

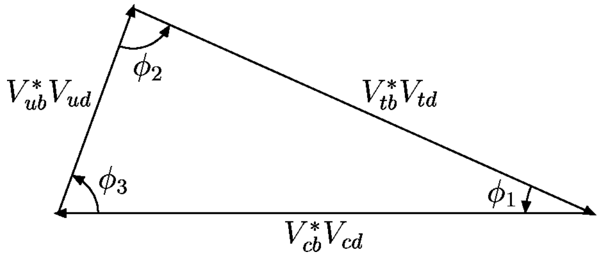

FIG. 1. The unitarity triangle.

time-dependent Dalitz analysis of $B \to \rho\pi$ [22]. $B \to D^{(*)}K^{(*)}$ modes provide us with the angle ϕ_3 [23]. $B \to D^{(*)}\pi$ [24] and $B \to D^*\rho$ [25] with the angular analysis give us information on $\sin(2\phi_1+\phi_3)$.

If we consider effects of new physics, these measurements can be interpreted as constraints on the phases of the B_d-$\overline{B}_d$ mixing and the decay amplitudes. When we neglect the new phases in the decay amplitudes, $B \to \pi\pi, \rho\pi$, $B \to D^{(*)}K^{(*)}$, and $B \to D^{(*)}\pi, D^*\rho$ provide us with $\sin(\phi_M+2\phi_3)$, ϕ_3, and $\sin(\phi_M+\phi_3)$, respectively, where ϕ_3 is the weak phase of the $b \to u$ transition amplitude in the standard phase convention given in the Appendix.[2] In the following analysis we assumed that ϕ_M is determined from the $B \to J/\psi K_S$ mode and related modes, and we study impacts of the ϕ_3 measurement on new physics search.

IV. NUMERICAL ANALYSIS

A. Parameters in the minimal supergravity model

In our calculation, the masses and the mixing matrices in the quark and lepton sectors are treated as input parameters which determine the Yukawa coupling matrices.

The CKM matrix elements V_{us}, V_{cb}, and $|V_{ub}|$ are determined in experiments independently of new physics contributions because these are extracted from tree-level processes. We fix V_{us} and V_{cb} in the following calculations as $V_{us}=0.2196$ and $V_{cb}=0.04$, and vary $|V_{ub}|$ within a range $|V_{ub}/V_{cb}|=0.09\pm 0.01$. Although the current error of $|V_{ub}|$ is estimated to be larger than this value, we expect theoretical and experimental improvements in the near future. We vary the CP violating phase, ϕ_3, within $\pm 180°$ because it is not constrained by the tree-level processes independently of new physics contributions. For the quark masses, we take $m_t^{\text{pole}}=175$ GeV, $m_b^{\text{pole}}=4.8$ GeV, $m_c^{\text{pole}}=1.4$ GeV, and $m_s^{\overline{\text{MS}}}(2\text{ GeV})=120$ MeV.

As for the SUSY parameters, we assume $M_{1/2}$, A_0, and μ are real parameters in order to avoid too large SUSY contributions to the electric dipole moments of the neutron and the electron. We vary these parameters within the ranges $0<m_0<3$ TeV, $0<M_{1/2}<1$ TeV, and $-5<A_0<5$ at the GUT scale. Both signs of μ are considered. We take the ratio of two VEVs $\tan\beta=\langle h_2\rangle/\langle h_1\rangle=20$ for most of our analysis and comment on other cases.

B. Parameters in the SU(5) SUSY GUT with right-handed neutrinos

In the SU(5) SUSY GUT with right-handed neutrinos, we need to specify the parameters in the neutrino sector in addition to the quark Yukawa coupling constants given in Sec. IV A. We take the neutrino masses as $m_{\nu_3}^2-m_{\nu_2}^2=2.4\times 10^{-3}$ eV^2, $m_{\nu_2}^2-m_{\nu_1}^2=4.2\times 10^{-5}$ eV^2, and $m_{\nu_1}\sim 0$, and the MNS matrix as

$$V_{\text{MNS}}=\begin{pmatrix} c_{\text{sol}}c_{13} & s_{\text{sol}}c_{13} & s_{13} \\ -s_{\text{sol}}c_{\text{atm}}-c_{\text{sol}}s_{\text{atm}}s_{13} & c_{\text{sol}}c_{\text{atm}}-s_{\text{sol}}s_{\text{atm}}s_{13} & s_{\text{atm}}c_{13} \\ s_{\text{sol}}s_{\text{atm}}-c_{\text{sol}}c_{\text{atm}}s_{13} & -c_{\text{sol}}s_{\text{atm}}-s_{\text{sol}}c_{\text{atm}}s_{13} & c_{\text{atm}}c_{13} \end{pmatrix}, \tag{30}$$

($c_i=\cos\theta_i$, $s_i=\sin\theta_i$) with $\sin^2 2\theta_{\text{atm}}=1$, $\sin^2 2\theta_{\text{sol}}=0.655$, and $\sin^2 2\theta_{13}=0.015$. These mass differences and mixing angles are consistent with the solar and atmospheric neutrino oscillations. The value of $\sin^2 2\theta_{13}$ is constrained by reactor experiments [26], and the above value is take as an illustration.

In addition, we assume that the mass matrix of the right-handed neutrino in Eq. (8) is proportional to the unit matrix, and we take $M_R=4\times 10^{13}$ GeV. Complex phases in the MNS matrix and the right-handed neutrino mass matrix are neglected.

The soft SUSY breaking parameters in this model are assumed to be universal at the Planck scale, and the running effect between the Planck and the GUT scales is taken into account. We scan the same ranges for m_0, $M_{1/2}$, and A_0 as those in the mSUGRA case.

C. Parameters in the U(2) model

In the U(2) model, we take the symmetry breaking parameters ϵ and ϵ' as $\epsilon=0.04$ and $\epsilon'=0.008$, and the other parameters in the quark Yukawa coupling matrices in Eq. (18) are determined so that the CKM matrix and the quark masses given in Sec. IV A are reproduced. Note that the texture of

[2]This approximation is valid for the three models under consideration, at least for $B \to D^{(*)}K^{(*)}, D^{(*)}\pi, D^*\rho$. New phases could be important for the decay amplitudes of $B \to \pi\pi, \rho\pi$. Even in such a case, we could obtain information about new phases by measuring CP asymmetries of the various modes listed above.

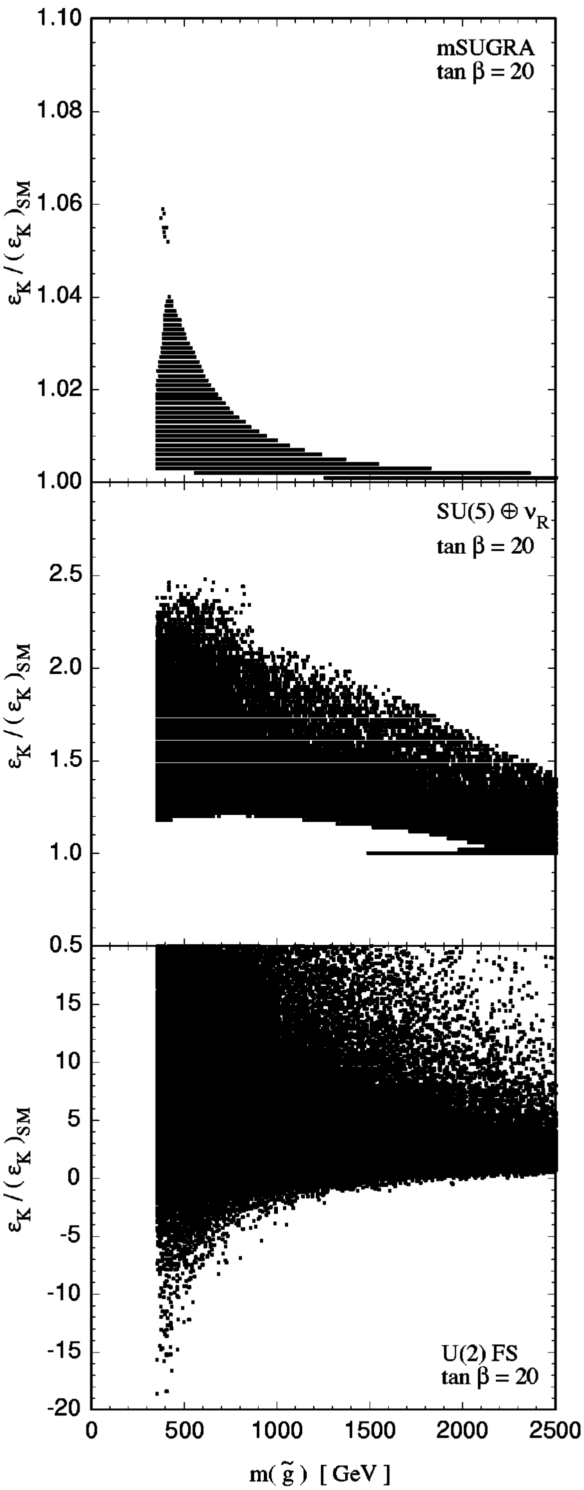

FIG. 2. Ratio of ε_K to the SM value as a function of the gluino mass for a fixed set of the parameters in the CKM matrix.

the Yukawa coupling matrices in Eq. (18) predicts the following relation among quark masses and CKM matrix elements:

$$\frac{m_u}{m_c}=\left|\frac{V_{ub}}{V_{cb}}\right|^2\left(1+\left|\frac{V_{ub}}{V_{cb}}\right|^2\right), \tag{31}$$

TABLE I. Decay constants and bag parameters for the B^0-$\overline{B^0}$ and the K^0-$\overline{K^0}$ mixing matrix elements used in the numerical calculation [20]. $\tilde{B}^{RR(2)}_{B_d,B_s}$ are given by $\tilde{B}^{RR(2)}_{B_q}=5\tilde{B}^{RR(1)}_{B_q}-4(m_{B_q}/m_b+m_q)^{-2}B_{B_q}$ with $q=d,s$, which is valid in the static limit.

f_K	B_K	$B_K^{LR(1)}$	$B_K^{LR(2)}$	$\tilde{B}_K^{RR(1)}$	$\tilde{B}_K^{RR(2)}$	
159.8 MeV	0.69	1.03	0.73	0.65	1.05	
f_{B_d}	f_{B_s}/f_{B_d}	B_B	$B^{LR(1)}_{B_d,B_s}$	$B^{LR(2)}_{B_d,B_s}$	$\tilde{B}^{RR(1)}_{B_d}$	$\tilde{B}^{RR(1)}_{B_s}$
210 MeV	1.17	0.8	0.8	0.8	0.8	1.19

$$\frac{m_d}{m_s}=\left|\frac{V_{td}}{V_{ts}}\right|^2\left(1+\left|\frac{V_{td}}{V_{ts}}\right|^2\right). \tag{32}$$

In the numerical calculation we adjust m_u and m_d to satisfy these relations.

There are many free parameters in the SUSY breaking sector as shown in Eqs. (20) and (21). In order to reduce the number of free parameters for numerical calculations, we assume that

$$m_0^{Q2}=m_0^{U2}=m_0^{D2}\equiv m_0^2, \tag{33}$$

$$r_{ij}^Q=r_{ij}^U=r_{ij}^D\equiv r_{ij},$$

$$(ij)=(22),(23),(33). \tag{34}$$

We vary these parameters within the ranges $0<m_0<3$ TeV, $-1<r_{22}<1$, $0<r_{33}<4$, $|r_{23}|<4$, and $-180°<\arg r_{23}<180°$. The boundary conditions for the A parameters and the slepton mass matrices are assumed to be the same as the mSUGRA case to simplify the numerical analysis. We think that the above assumptions on the soft breaking terms are sufficient for our purpose of comparing new physics effects related to the B^0-$\overline{B^0}$ and the K^0-$\overline{K^0}$ mixings in the three models.

D. Experimental constraints

In order to obtain allowed parameter regions, we impose the following experimental constraints:

Lower limits on the masses of SUSY particles and the Higgs bosons given by the direct search in collider experiments [27].

Branching ratio of the $b\to s\gamma$ decay: $2\times10^{-4}<B(b\to s\gamma)<4.5\times10^{-4}$ [28].

Branching ratio of the $\mu\to e\gamma$ decay for the SUSY GUT case: $B(\mu\to e\gamma)<1.2\times10^{-11}$ [29].

Measured values of ε_K and Δm_{B_d} [30], and the lower bound of Δm_{B_s} [31].

CP asymmetry in the $B\to J/\psi K_S$ decay and related modes observed in the B factory experiments [1,2].

Although the values of ε_K and Δm_{B_d} are precisely measured in experiments, there are theoretical uncertainties in the evaluation of the matrix elements for $\Delta S(B)=2$ operators.

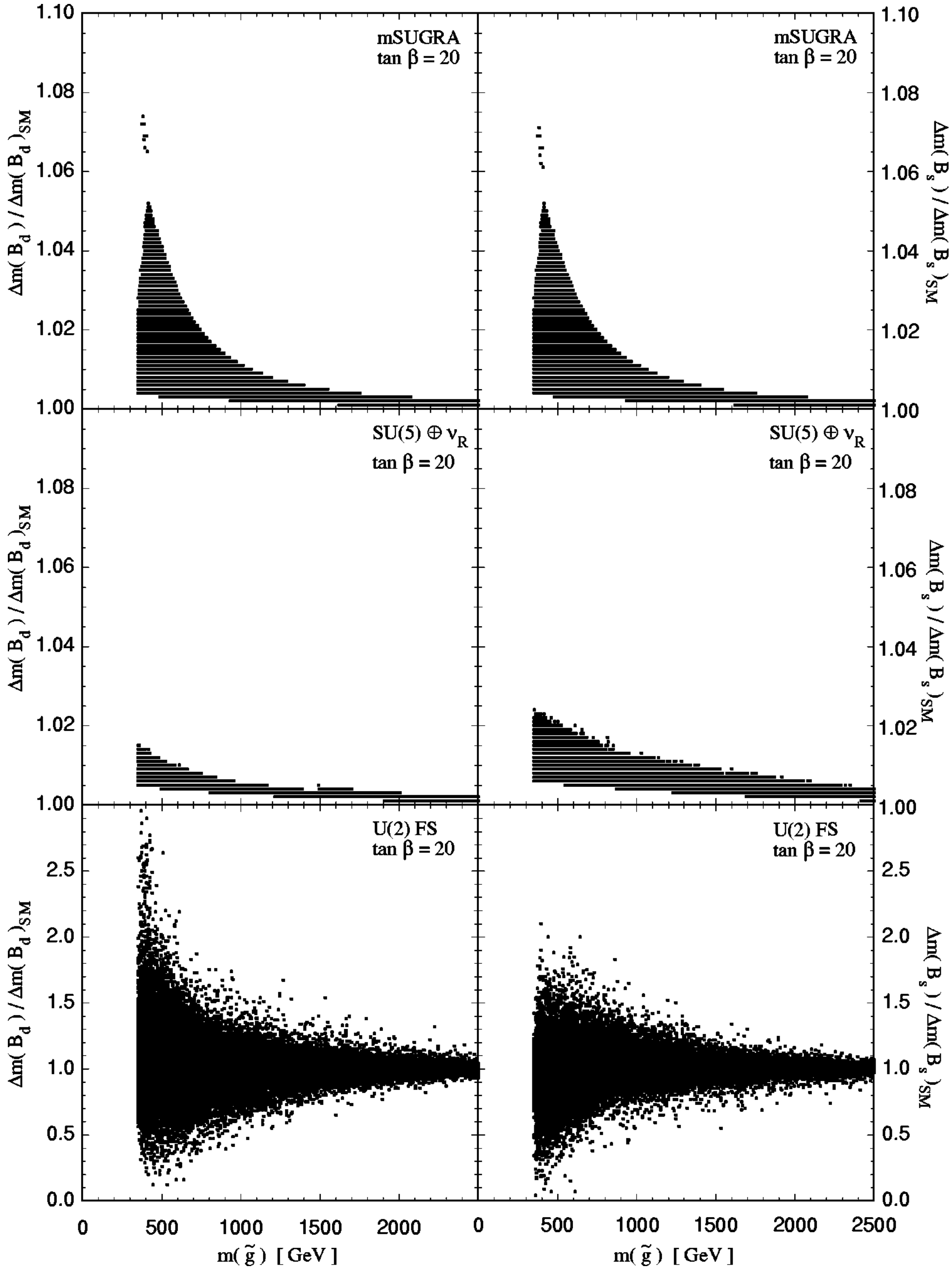

FIG. 3. Deviations of Δm_{B_d} and Δm_{B_s} from the SM values as functions of the gluino mass with the same parameter set as Fig. 2.

In order to take these theoretical uncertainties into account, we calculate ε_K and Δm_{B_d} with bag parameters and $f_{B_{d,s}}$ in Table I and allow parameter sets if the calculated values of ε_K and Δm_{B_d} lie within the ranges

$$\varepsilon_K = e^{i\pi/4}(2.28\times 10^{-3})\times(1\pm 0.15), \tag{35}$$

$$\Delta m_{B_d} = 0.479\,\mathrm{ps}^{-1}\times(1\pm 0.2)^2. \tag{36}$$

For Δm_{B_s}, we impose a constraint on the ratio to Δm_{B_d} as $\Delta m_{B_s}/\Delta m_{B_d} > 27$ since a large portion of the theoretical uncertainties is expected to cancel by taking the ratio. For the CP asymmetry, we use $A_{CP}^{\mathrm{mix}}(B\to J/\psi K_S) > 0.5$.

E. Numerical results

At first we discuss qualitative features of the SUSY contributions to the B_d-$\overline{B}_d$ mixing, the B_s-$\overline{B}_s$ mixing, and ε_K for each model.

In the mSUGRA, it is well known that the main SUSY contributions to $M_{12}(B_d)$, $M_{12}(B_s)$, and $M_{12}(K)$ come from the box diagrams with the charginos and the up-type squarks and that the flavor mixing in the chargino vertex is determined by the CKM matrix. Consequently, the SUSY contributions are approximately proportional to the CKM matrix elements $(V_{td}^* V_{tb})^2$, $(V_{ts}^* V_{tb})^2$, and $(V_{td}^* V_{ts})^2$ for $M_{12}(B_d)$, $M_{12}(B_s)$, and $M_{12}(K)$, respectively, and the ratios to the corresponding SM contributions are common:

$$\frac{(\Delta m_{B_d})_{\rm SUSY}}{(\Delta m_{B_d})_{\rm SM}} = \frac{(\Delta m_{B_s})_{\rm SUSY}}{(\Delta m_{B_s})_{\rm SM}} \approx \frac{(\varepsilon_K)_{\rm SUSY}}{(\varepsilon_K)_{\rm SM}}. \tag{37}$$

For the other two models, this proportionality is violated due to the squark flavor mixing induced by sources other than the CKM matrix.

In the SU(5) SUSY GUT with right-handed neutrinos, the flavor mixing in the right-handed down-type squark sector is related to the flavor mixing in the left-handed slepton sector, and hence the constraints from the lepton flavor violating processes such as $\mu \to e\gamma$ is important. As shown in Ref. [14], $B(\mu \to e\gamma)$ exceeds the present experimental upper limit 1.2×10^{-11} in the parameter region where the SUSY contributions to the B^0-$\overline{B}^0$ mixings become larger than $\simeq 10\%$.[3] Therefore Δm_{B_d}, Δm_{B_s}, and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$ are almost the same as the SM values for a given CKM matrix. On the other hand, ε_K can be quite different from the SM value even under the $\mu \to e\gamma$ constraint because of large enhancements of the K^0-$\overline{K}^0$ mixing matrix elements for the scalar operators in Eq. (24). This correction of ε_K leads to a change of the allowed region of the parameter ϕ_3 and eventually affects the possible region of $\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$.

In the U(2) model, the SUSY contribution to ε_K can be large in a similar manner. In addition, there are $O(1)$ corrections to $M_{12}(B_d)$ and $M_{12}(B_s)$ so that the $\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$ can be different from the SM values with the same CKM matrix.

Deviations of ε_K, Δm_{B_d}, Δm_{B_s}, and ϕ_M from the SM values are plotted as functions of the gluino mass for $\tan\beta = 20$ in Figs. 2–4. In these figures, we fix the parameters in the CKM matrix as $|V_{ub}/V_{cb}| = 0.09$ and $\phi_3 = 65°$ and do not impose the experimental constraints from ε_K, Δm_{B_d}, Δm_{B_s}, and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$. The above features can be seen quantitatively in these figures. We see that ε_K can be different from the SM prediction by a factor of $\simeq 2.5$ in the SU(5) SUSY GUT with right-handed neutrinos, and the deviation is even larger in the U(2) model. In the mSUGRA, the deviation is smaller than 10%. As for Δm_{B_d} and Δm_{B_s}, $O(1)$ deviations are possible in the U(2) model, while the deviations are small for the other cases. The value of ϕ_M can also be different from the SM value ($=2\phi_1$) significantly in the case of the U(2) model. For the mSUGRA and the SU(5) SUSY GUT with right-handed neutrinos, $\phi_M = 2\phi_1$ is a good approximation.

Next, let us vary $|V_{ub}/V_{cb}|$ and ϕ_3 and impose all the experimental constraints explained above. In Fig. 5 we show possible values of $A_{CP}^{\rm mix}(B \to J/\psi K_S)$, $\Delta m_{B_s}/\Delta m_{B_d}$, and ϕ_3

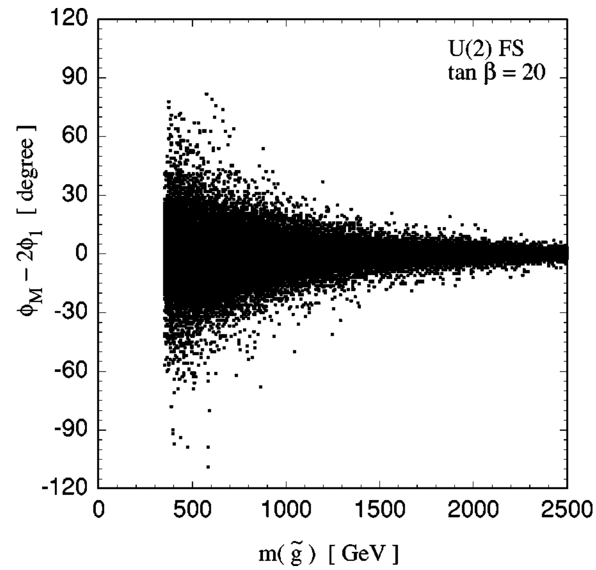

FIG. 4. Deviation of ϕ_M from the SM value ($=2\phi_1$) as a function of the gluino mass for the U(2) model with the same parameter set as Fig. 2.

for the parameter sets satisfying the constraints. The corresponding allowed region for the SM is also given in each plot. Solid curves show the correlations among three quantities in the SM for $|V_{ub}/V_{cb}| = 0.08$, 0.09, and 0.10. We see that the allowed region in the SM is mainly determined by $|V_{ub}/V_{cb}|$ and ε_K.

In the mSUGRA, the deviation from the SM is not so significant since the SUSY contributions to all the M_{12}'s are small.

In the SU(5) SUSY GUT with right-handed neutrinos, we see that all the allowed points lie between the lines corresponding to the SM values with $|V_{ub}/V_{cb}| = 0.08$ and 0.10. This pattern arises because only the K^0-$\overline{K}^0$ mixing receives SUSY corrections of $O(1)$ corrections from the SUSY loops, whereas the SUSY contributions to $M_{12}(B_d)$ and $M_{12}(B_s)$ are small. As a result, the allowed region of ϕ_3 can be shifted, and $\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$ can be different from the SM region. In other words, observables from B physics namely $|V_{ub}/V_{cb}|$, $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{CP}^{\rm mix}(B \to J/\psi K_S)$, and ϕ_3 consistently determine a set of parameters in the CKM matrix in the SM analysis, though the experimental value ε_K may not be consistent with the SM value calculated by the CKM parameters from B physics. The upper limit of $\Delta m_{B_s}/\Delta m_{B_d}$ in the plot is determined by the lower bound of Δm_{B_d} given in Eq. (36).

In the U(2) model, we see that the allowed points exist outside of the region between $|V_{ub}/V_{cb}| = 0.09 \pm 0.01$ lines. SUSY corrections to $M_{12}(B_d)$ and $M_{12}(B_s)$ in this model, unlike those in the SUSY GUT, are considerably large and not proportional to the corresponding combinations of CKM elements in the SM. Since all of ε_K, $\Delta m_{B_s}/\Delta m_{B_d}$, and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$ can be corrected, there might be a mismatch in the determination of the unitarity triangle by the SM analysis with these quantities and ϕ_3. In particular, we

[3] The constraint from $B(\mu \to e\gamma)$ is somewhat model dependent. The above results depend on our choice of the structure of M_N and/or $V_{\rm MNS}$. If we change these assumptions and suppress $B(\mu \to e\gamma)$, the SUSY contribution to Δm_{B_s} can be more significant. For example, if we take the small mixing MSW solution for the solar neutrino anomaly, a 50% enhancement of Δm_{B_s} is possible [14].

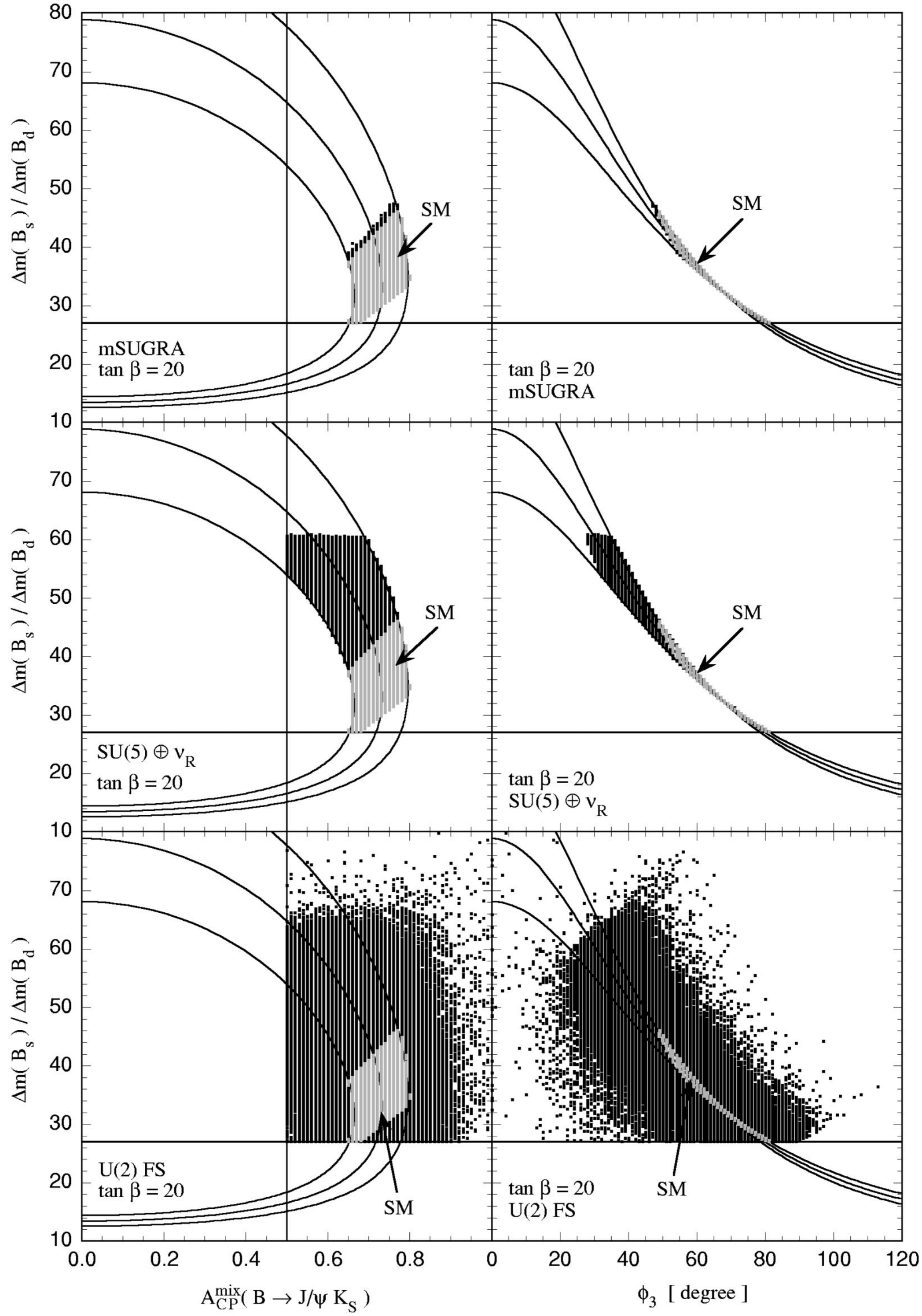

FIG. 5. Scatter plots in the planes $[A_{CP}^{\mathrm{mix}}(B\to J/\psi K_S),\Delta m_{B_s}/\Delta m_{B_d}]$ and $(\phi_3,\Delta m_{B_s}/\Delta m_{B_d})$ for three SUSY models. Solid curves show the SM values with fixed $|V_{ub}/V_{cb}|=0.08$, 0.09, and 0.10.

may be able to extract new physics contributions from observables in B physics.

Finally, we discuss future prospects of new physics search in B decays. We expect that $A_{CP}^{\mathrm{mix}}(B\to J/\psi K_S)$ and $\Delta m_{B_s}/\Delta m_{B_d}$ will be precisely measured in a few years at the B factories and Tevatron experiments. If we assume the SM, CKM parameters, especially ϕ_3, can be determined from these observables with small hadronic uncertainties. By comparing this ϕ_3 value with that derived from CP asymmetries in various B decays, we can carry out a consistency check of the SM and examine the existence of SUSY effects. As an illustration, we pick up the calculated data points which sat-

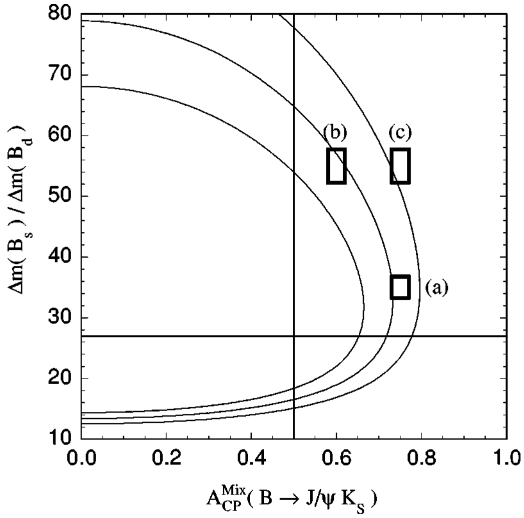

FIG. 6. Typical example regions. (a) $\Delta m_{B_s}/\Delta m_{B_d}=35\times(1\pm0.05)$ and $A_{CP}^{\rm mix}(B\to J/\psi K_S)=0.75\pm0.02$. (b) $\Delta m_{B_s}/\Delta m_{B_d}=55\times(1\pm0.05)$ and $A_{CP}^{\rm mix}(B\to J/\psi K_S)=0.60\pm0.02$. (c) $\Delta m_{B_s}/\Delta m_{B_d}=55\times(1\pm0.05)$ and $A_{CP}^{\rm mix}(B\to J/\psi K_S)=0.75\pm0.02$.

isfy the following values of $A_{CP}^{\rm mix}(B\to J/\psi K_S)$ and $\Delta m_{B_s}/\Delta m_{B_d}$:

(a) $\Delta m_{B_s}/\Delta m_{B_d}=35\times(1\pm0.05)$,

$$A_{CP}^{\rm mix}(B\to J/\psi K_S)=0.75\pm0.02,$$

(b) $\Delta m_{B_s}/\Delta m_{B_d}=55\times(1\pm0.05)$,

$$A_{CP}^{\rm mix}(B\to J/\psi K_S)=0.60\pm0.02,$$

(c) $\Delta m_{B_s}/\Delta m_{B_d}=55\times(1\pm0.05)$,

$$A_{CP}^{\rm mix}(B\to J/\psi K_S)=0.75\pm0.02.$$

(a) corresponds to the case in which ε_K, $A_{CP}^{\rm mix}(B\to J/\psi K_S)$, and $\Delta m_{B_s}/\Delta m_{B_d}$ are consistent with the SM. (b) and (c) are cases in which there are some inconsistencies among the three observables within the SM. The three regions are shown in Fig. 6.

We present the possible region of ϕ_3 in each case for the three models in Fig. 7. For the case (a), ϕ_3 is 60°–65° if we

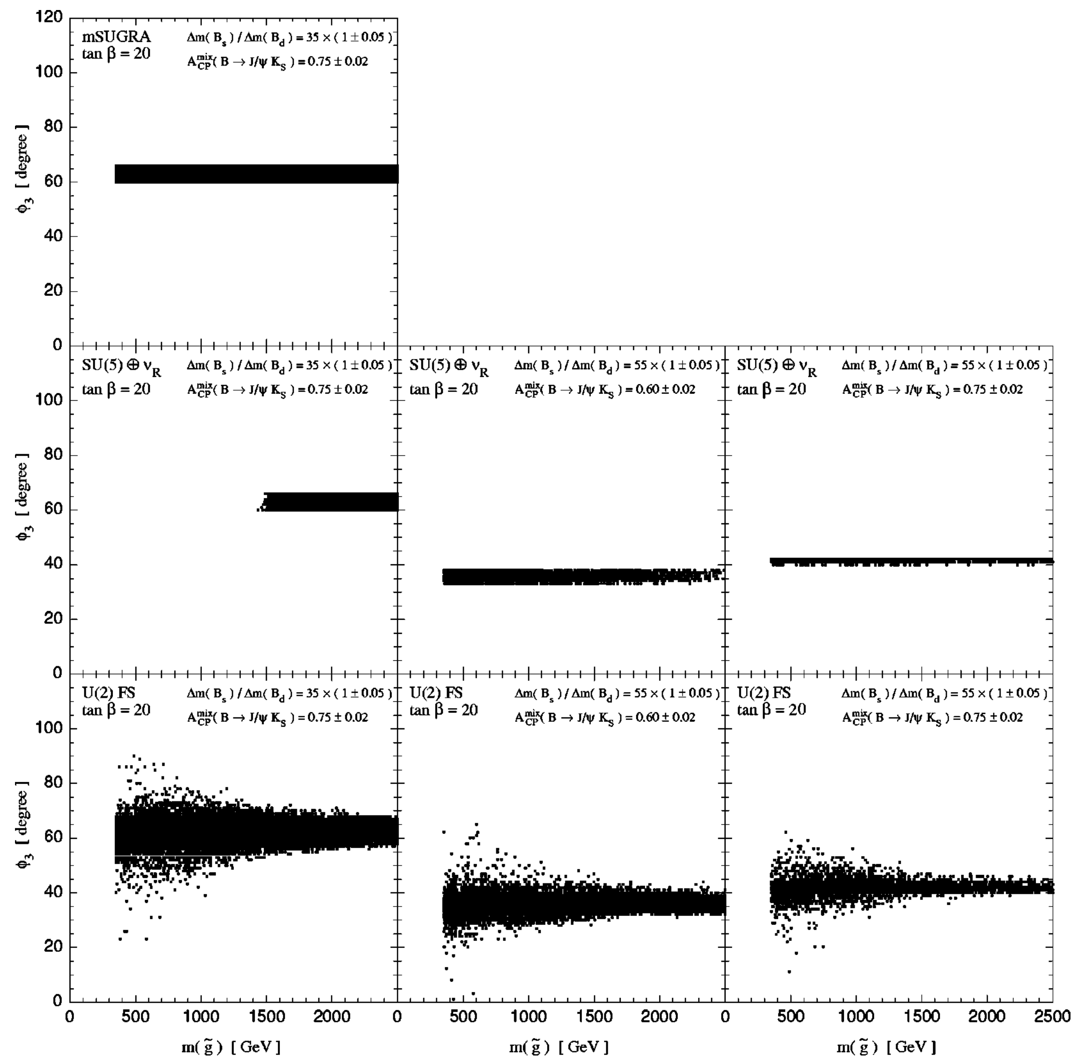

FIG. 7. Possible region of ϕ_3 as a function of the gluino mass.

assume the SM. The possible value of ϕ_3 is the same as the SM in the mSUGRA and the SU(5) SUSY GUT with right-handed neutrinos. The parameter region with $m_{\tilde{g}} \lesssim 1.5$ TeV in the SU(5) SUSY GUT is excluded due to the $\mu \to e\gamma$ constraint. On the other hand, in the U(2) model, ϕ_3 can be different from the SM value by $\sim 30°$ for the $m_{\tilde{g}} \lesssim 1$ TeV region.

For the cases (b) and (c), the mSUGRA (as well as the SM) is excluded because of the mismatch among ε_K, $A_{CP}^{\rm mix}(B \to J/\psi K_S)$, and $\Delta m_{B_s}/\Delta m_{B_d}$. In the other two models, the experimental value of ε_K can be reproduced with SUSY contributions. In the SU(5) SUSY GUT with right-handed neutrinos, ϕ_3 is the same as that derived from $\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$ by the SM analysis. In the U(2) model, ϕ_3 can be different from the value of the SM.

We have also studied the case of $\tan\beta = 5$ and drawn the figures corresponding to Figs. 5 and 7. We have found that the allowed regions in these figures are almost the same as those for $\tan\beta = 20$.

V. CONCLUSIONS

In order to distinguish SUSY models by measurements at B factories, we have studied SUSY contributions to the K^0-$\overline{K}^0$, B_d-$\overline{B}_d$, and B_s-$\overline{B}_s$ mixings in three SUSY models, namely the mSUGRA, the SU(5) SUSY GUT with right-handed neutrinos, and the U(2) model.

First, we have considered the observables Δm_{B_d}, Δm_{B_s}, $A_{CP}^{\rm mix}(B \to J/\psi K_S)$, and ε_K. In the mSUGRA, the deviations from the SM values are at most 10% for these observables. In the SU(5) SUSY GUT with right-handed neutrinos, the SUSY contributions to ε_K can be large whereas those to $M_{12}(B_d)$ and $M_{12}(B_s)$ are less than 10%. In the U(2) model, the deviations from the SM values for all the above observables can be very large. In the latter two models, we may be able to see SUSY effects from the consistency check of the unitarity triangle among ε_K, $\Delta m_{B_s}/\Delta m_{B_d}$, and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$.

Second, we have considered cases in which the two observables $\Delta m_{B_s}/\Delta m_{B_d}$ and $A_{CP}^{\rm mix}(B \to J/\psi K_S)$ are precisely determined at the B factories and Tevatron experiments. We have studied how we can distinguish these different models if we determine ϕ_3 in addition to the above two observables. We can carry out the consistency check of the unitarity triangle among the observables in B physics, namely $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{CP}^{\rm mix}(B \to J/\psi K_S)$, and ϕ_3. For the U(2) model, in particular, a large deviation from the SM value is possible. It is therefore very important to determine ϕ_3 precisely in theoretically clean ways from the decay modes, such as $B \to \pi\pi, \rho\pi, D^{(*)}K^{(*)}, D^{(*)}\pi, D^*\rho$. These measurements are possible in future e^+e^- super B factories and hadron machines such as LHC-B and B-TeV.

In this paper we have mainly considered the consistency test of the unitarity triangle through B_d decays, but there are other possibilities of finding SUSY effects in B physics. A new phase in the B_s-$\overline{B}_s$ mixing amplitude may affect CP asymmetries in B_s decays such as the $B_s \to J/\psi\phi$ decay. These asymmetries can be measured in B experiments at hadron machines. For the U(2) model, these CP asymmetries could be different from the SM prediction [15]. Another possibility is to measure branching ratios and CP asymmetries in rare decays such as $b \to s l^+ l^-$ and $b \to s\nu\overline{\nu}$.

In conclusion we have shown that SUSY models with different flavor structures can be distinguished in B physics. As we have illustrated with three specific models, the patterns of the deviations from the SM in the B physics depend on the SUSY breaking mechanism and interactions at a high energy scale. Present and future experiments in B physics at e^+e^- B factories and hadron machines are therefore very important to explore the flavor structure of SUSY breakings.

Note added. After submission of this paper, we received the paper by D. Chang, A. Masiero, and H. Murayama [33] in which the possibility of the large $b-s$ transition is pointed out in the context of the SO(10) SUSY GUT.

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APPENDIX: THE CKM MATRIX AND THE UNITARITY TRIANGLE

In this paper we use the "standard" parametrization [32] for the CKM matrix with three mixing angles θ_{12}, θ_{23}, θ_{13} and a complex phase δ_{13}:

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}, \tag{A1}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. The angles ϕ_1, ϕ_2, and ϕ_3 in the unitarity triangle are defined as

$$\phi_1 = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}} \right), \tag{A2a}$$

$$\phi_2 = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right), \tag{A2b}$$

$$\phi_3 = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \right). \tag{A2c}$$

In the convention (A1), these angles are written in a good approximation as

$$\phi_1 = \frac{1}{2} \arg M_{12}^{\mathrm{SM}}(B_d), \tag{A3}$$

$$\phi_3 = \delta_{13}. \tag{A4}$$

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